



Arnold Schwarzenegger  
*Governor*

# BIOMASS-TO-SYNGAS, NOVEL LOW-COST COUNTER-CURRENT PROCESS

## INDEPENDENT ASSESSMENT REPORT

*Prepared For:*

**California Energy Commission**

Public Interest Energy Research Program

Energy Innovations Small Grants Program

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## PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to \$62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)

- Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: <http://www.energy.ca.gov/research/innovations> or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: [eisgp@energy.state.ca.us](mailto:eisgp@energy.state.ca.us).

For more information on the overall PIER Program, please visit the California Energy Commission's website at <http://www.energy.ca.gov/research/index.html>.

## Abstract

More than 31 million tons of organic material, including: paper, wood, and urban green waste, were disposed of in California landfills in 2003. Thermal conversion technologies are an attractive alternative to land-filling and could provide much needed electricity as a renewable fuel, while avoiding the equivalent use of oil, coal, or natural gas. The 85,000 tons per day of organic feedstock are enough to produce 4,000 MW of electricity. The dollar-value of these California feed-stocks, when converted into electricity is valued at \$0.05 per kWh, and is equal to \$200,000 per hour, or \$ 1.6 billion per year.

The researcher proposed a novel gasification hardware and methodology that was projected to address an existing market opportunity by providing a low-cost alternative to existing thermal conversion technologies which are not presently cost-effective. A specific project objective was to design and fabricate a low-cost one million Btu per hour gasification reactor, verify performance of the reactor by measuring operating parameters, including temperature, pressure, gas-flow rates, and gas composition. The cost goals were 5 cents per kWh for the operating cost, including a system capital cost goal of \$18,000 per ton per day capacity, projected for a 50 ton per day feed capacity system.

The project information has been used to design a Transport Reactor at farm-scale that was under construction in 2005, and would operate during 2006 for extended campaigns to predict long-term economic performance. The cost was \$300,000 for a small farm-scale system designed to feed six ton per day, powering a 300 kW Cummins engine-generator, and intended for continuous duty. The projected operating cost was approximately \$0.05 per kWh when the biomass feedstock has near-zero cost or negative-value when sourced from agricultural and urban residues. The pilot-scale gasification hardware constructed and started-up during the performance of this work was being tested to obtain supporting data to be used for the design of a biomass-to-hydrogen system.

**Keywords:** gasification, conversion, biomass, entrained-flow, renewable, bio-energy, biofuels

## Introduction

More than 31 million tons of organic material, including paper, wood, and urban green waste, were disposed of in California landfills in 2003.<sup>1</sup> Thermal conversion of organic waste is an attractive alternative to disposal in landfills and could generate electricity and/or renewable fuels for transportation, while avoiding the equivalent use of oil, coal, and natural gas. The 85,000 tons/day of organic feedstock are enough to produce approximately 4,000 MW of electricity. The dollar-value of these California feedstocks, if converted into electricity valued at \$0.05/kWh, would equal \$200,000 per hour, or \$1.6 billion per year. Five cents per kWh is the value of generation portion of the retail price of electricity of approximately \$0.13/kWh. At the present time there are few cost effective thermo-chemical conversion technologies available to fill this California market need.

Ratepayers would benefit significantly from the use of biomass energy resources produced in California. The first benefit is the production of energy products within the State of California. These products would add diversity to the source of energy for ratepayers and thus provide greater energy reliability. The second benefit is the reduction in material deposited in landfills. This will extend the life of existing landfills and possibly reduce the quantities of landfill off-gases escaping into the environment. Major portions of landfill gases are considered to be greenhouse gases. Another potential benefit from gasification technology is the ability to convert difficult-to-handle solid fuels into clean gaseous fuel that can then be burned in traditional prime movers, including large internal combustion engines and gas turbines; in emerging technologies such as solid oxide fuel cells (SOFC); or in production of liquid fuels.

Taylor Energy, LLC proposed a novel gasification method for organic materials. Its major advantage would be the capability of producing synthesis gas from organic materials without using manufactured oxygen (made by consuming electricity). As shown in Figure 1, the proposed gasification reactor vessel was constructed of off-the shelf pre-flanged ductile iron components. The proposed gasification system had the potential to have lower capital cost compared to other gasification technologies.

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<sup>1</sup> <http://www.ciwmb.ca.gov/Profiles/Statewide/SWProfile1.asp>

Drawn By: Charles Beavis  
( Modified By: Chris Holp )  
1 March 2005



## Objectives

This project was to prove the feasibility of a novel biomass-to-syngas process specifically designed for low-cost conversion of biomass into high-quality syngas suitable for SOFC power generation. The principal investigator established the following project objectives:

1. Produce syngas from 3 different feedstocks in a 1 MMBTU/hr test reactor with:
  - a) 5-10 percent N<sub>2</sub> content
  - b) <1 percent O<sub>2</sub>
  - c) 1-5 percent CH<sub>4</sub>
  - d) Energy Content of 200-350 BTU/scf
  - e) Quality of 12.0 or higher ((H<sub>2</sub> +CO)/ (CO<sub>2</sub>+H<sub>2</sub>O))The product gases were assumed to be filtered at atmospheric temperature in commercial application, and therefore tars, particulate, and alkali metals were not considered problematic and were not identified in the performance criteria.
2. Verify thermal conversion efficiency for biomass to syngas of 50 percent, with total conversion to electricity efficiency of 30 percent.
3. Extrapolate bench scale data to the farm scale and confirm projected system conversion efficiency of 70 percent (biomass-to-syngas) with total conversion to electricity of 42 percent.
4. Demonstrate projected cost of 3-5 cents/kWh and total capital cost of \$18k/ (ton/day) for farm scale units.

## Outcomes

1. The researcher tested chopped-straw in a 1 MMBTU/hr test-reactor at a rate of three ton/day with the following results:
  - a) >50% N<sub>2</sub> content
  - b) <2% O<sub>2</sub>
  - c) 1-5% CH<sub>4</sub>
  - d) Energy Content = 110-120 BTU/scf
  - e) Syngas quality was not calculated, nor was the conversion efficiency.
2. The researcher did not demonstrate thermal conversion efficiency of 50 percent for biomass-to-syngas, nor total conversion to electricity of 30 percent efficiency. The researcher did not measure biomass-to-syngas conversion efficiency.
3. The researcher designed a farm-scale Process Development Unit (PDU—six ton/day, 300 kW electric), and he produced simple CAD drawings. The PDU was designed for continuous operation and long-term life cycle projections. The researcher did not project conversion efficiency.
4. The projected cost for small-scale gasification equipment approached the performance objective of \$18k/ton/day feed capacity; therefore, the researcher expected scaling the equipment to 50 ton/day (2 MW<sub>e</sub> output) to be economically feasible, based on cost quotations for 6 ton/day PDU. The researcher estimated an electricity cost of \$0.05/kWh if the biomass feedstock cost is zero.
5. The researcher determined performance parameters for the circulation system. Each of six bed materials were circulated effectively in the test-reactor at temperatures above 1200° F, with circulation rates exceeding four pounds per second when compressed air input was 150 scfm.

6. The researcher successfully demonstrated a novel, low-cost reactor construction method, using off-the-shelf flanged cast-iron spool-sections that bolt together. Tests proved heavy duty, ductile-iron pipe sections useful for high temperature applications at temperatures under 1350° F and atmospheric pressures.

## **Conclusions**

This project did not establish the preliminary feasibility of the novel gasification reactor concept proposed.

1. The syngas product is neither useable in solid oxide fuel cells, nor in many traditional internal combustion engines nor turbines. It would require extensive cleanup and further processing in order to be feedstock for most liquid fuel production, including the Fischer Tropsch process. The high nitrogen content of the syngas could lead to high NO<sub>x</sub> emissions. In addition, fuels with extremely low energy content are difficult, if not impossible, to burn in standard combustion systems.
2. Thermal conversion efficiency of 50 percent for biomass-to-syngas, with total conversion to electricity with 30 percent efficiency was not achieved. Low conversion efficiencies usually lead to larger, more expensive energy systems. Thus, very low conversion efficiency will likely offset any potential capital cost savings.
3. The researcher designed the PDU for continuous operation and long-term life cycle projections. Because the researcher did not calculate conversion efficiency it is difficult to determine the value of this unit.
4. While the researcher's projected cost numbers are near his goal, he may not have considered the effects of low conversion efficiency and high fuel nitrogen content.
5. The researcher successfully demonstrated effective bed circulation rates at temperatures up to 1350° F. The researcher demonstrated circulation rates of four pounds per second with air input of 150 scfm. Good circulation rates at elevated temperatures are important performance features necessary to avoid blocking the fuel circulation (e.g. from slagging or melting bed materials into large lumps) and to maintain gasification thermal profiles within the reactor.
6. The test did not demonstrate if the ductile iron would be effective in real-world gasification applications with higher gasifying atmospheres.

The tests conducted did not demonstrate the feasibility of the concept to lower the cost of gasification technologies for integration with solid-oxide fuel cells. Its feasibility for other power generation technologies, such as internal combustion or turbine based systems is questionable. The fabrication approach of using pre-fabricated spool sections shows promise to reduce costs, but the use of ductile iron in hot sections under conditions of gasifying atmospheres is questionable.

## **Recommendations**

The researcher should monitor and document performance of the PDU with respect to conversion efficiency. Operating conditions that affect conversion efficiency should be determined and operating conditions that maximize conversion efficiency should be validated. The researcher should also determine performance with bed recirculation to determine ability to reduce char. The researcher should investigate techniques to reduce nitrogen in the produced syn-gas. Further research and development, if otherwise warranted, should include evaluating pre-fabricated spools composed of materials other than ductile iron, and tested in conjunction

with gasifying atmospheres with appropriate gas clean-up. Such tests should, at minimum determine carry-through of tars, particulate, and alkali metals; gas product quality; and biomass to syngas conversion efficiency.

### **Benefits to California**

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. This benefit would result from increased diversification of fuels used in generation of electricity and by making use of otherwise waste materials. In addition to increased affordability, this project should benefit California ratepayers by reducing the environmental impacts of electricity supply system, by the use of non-fossil fuels. This project also furthers the advancement of science technology by demonstrating greater cost reduction that can be achieved through innovative construction approaches, especially the use of pre-fabricated gasifier sections.

## **Overall Technology Transition Assessment**

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

### **Marketing/Connection to the Market**

The project failed to demonstrate the feasibility of the concept. Therefore, there does not appear any connection to the market at this time. The researcher has not published a technical paper describing this work. The researcher has designed a farm-scale unit for scale-up testing from the pilot-scale unit described here.

### **Engineering/Technical**

The project failed to demonstrate the technical feasibility of the concept. The fabrication approach shows promise for capital cost reduction. Further research and development, if otherwise warranted, should include evaluating pre-fabricated spools composed of materials other than ductile iron, and tested in conjunction with gasifying atmospheres with appropriate gas clean-up. Such tests should, at minimum determine carry-through of tars, particulate, and alkali metals; gas product quality; and biomass to syngas conversion efficiency.

### **Legal/Contractual**

The project failed to demonstrate the feasibility of the concept and therefore there does not appear any need for patent or other legal protection. The researcher had not applied for patents.

### **Environmental, Safety, Risk Assessments/ Quality Plans**

The project failed to demonstrate the feasibility of the concept and therefore environmental and safety risk assessment and quality plans are premature.

### **Production Readiness/Commercialization**

Until the feasibility of the concept is proven it is premature to discuss production readiness.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

# **ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM**

## **EISG FINAL REPORT**

**Biomass-to-Syngas, Novel Low-Cost Counter-Current Process**

### **EISG AWARDEE**

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PIER Subject Area: Renewable Energy Technologies

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email [eisgp@energy.state.ca.us](mailto:eisgp@energy.state.ca.us).

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## **Abstract**

More than 31 million tons of organic material, including paper, wood, and urban green waste, were disposed of in California landfills in 2003. Thermal conversion technologies are an attractive alternative to landfilling and could provide much needed electricity and Renewable Fuels, while avoiding the equivalent use of oil, coal, and natural gas. The 85,000 tons/day of organic feedstock are enough to produce 4,000 MW of electricity. The dollar-value of these California feedstocks, when converted into electricity valued at \$0.05/kWh, is equal to \$200,000 dollars per hour, or \$ 1.6 billion dollars per year.

Taylor Energy LLC has proposed novel gasification hardware and methodology that is projected to address this existing market opportunity by providing a low-cost alternative to existing thermal conversion technologies which are not presently cost-effective. A specific project objective was to design and fabricate a low-cost 1 MM BTU/hr gasification reactor, verify performance of the reactor by measuring operating parameters, including temperature, pressure, gas-flow rates, and gas composition. The cost goals were 5 cents per kWh for the operating cost, including a system capital cost goal of \$18,000/(ton/day) capacity, projected for a 50 ton/day feed capacity system.

The project information has been used to design a Transport Reactor at farm-scale that is under construction in 2005, and will operate during 2006 for extended campaigns to predict long-term economic performance. The cost is \$300,000 for a small farm-scale system designed to feed 6 ton/day, powering a 300 kW Cummins engine-generator, and intended for continuous duty. The projected operating cost is approximately \$0.05/kWh when the biomass feedstock has near-zero cost or negative-value when sourced from agricultural and urban residues. The pilot-scale gasification hardware constructed and started-up during the performance of this work is being tested to obtain supporting data to be used for the design of a biomass-to-hydrogen system.

**Key Words:** gasification, conversion, biomass, entrained-flow, renewable, bioenergy, biofuels

# Executive Summary

## Introduction

More than 31 million tons of organic material, including paper, wood, and urban green waste, were disposed of in California landfills in 2003. Thermal conversion technologies are an attractive alternative to landfilling and could provide much needed electricity and Renewable Fuels, while avoiding the equivalent use of oil, coal, and natural gas. The 85,000 tons/day of organic feedstock are enough to produce 4,000 MW of electricity. The dollar-value of these California feedstocks, when converted into electricity valued at \$0.05/kWh, is equal to \$200,000 dollars per hour, or \$ 1.6 billion dollars per year.

However, at the present time there are few commercially viable thermochemical conversion technologies available to fill this California market need. Taylor Energy LLC has proposed novel gasification hardware and methodology to provide a low-cost pathway to synthesis gas production without using costly oxygen that is made by consuming electricity.

## Project Objectives

The goal of this project was to demonstrate the feasibility of a novel biomass-to-syngas process specifically designed for low-cost conversion of biomass into high-quality syngas suitable for Solid Oxide Fuel Cell (SOFC) power generation.

1. Produce syngas from 3 different feedstocks in a 1 MMBTU/hr test reactor with:

- a. 5-10% N<sub>2</sub> content
- b. <1% O<sub>2</sub>
- c. 1-5% CH<sub>4</sub>
- d. Energy Content = 200-350 BTU/scf
- e. Quality of 12.0 or higher ((H<sub>2</sub> +CO)/(CO<sub>2</sub>+H<sub>2</sub>O))

The product gases are filtered at atmospheric temperature, and therefore tars, particulate, and alkali metals are not problematic to remove and are not identified in the performance criteria.

2. Verify thermal conversion efficiency for biomass to syngas of 50%, with total conversion to electricity efficiency of 30%.

3. Extrapolate bench scale data to the farm scale and confirm projected system conversion efficiency of 70% (biomass-to-syngas) with total conversion to electricity of 42%.

4. Demonstrate projected cost of 3-5 cents/kWh and total capital cost of \$18k/(ton/day) for farm scale units.

## Project Outcomes

The preliminary feasibility of a novel gasification reactor concept was verified by constructing and operating a test-reactor at large bench-scale. EISG funds were leveraged into a total \$375k project budget and were used to construct the subject test-reactor and perform start-up testing to establish preliminary feasibility. The top section of the test reactor is shown in **Figure 1**, and the biomass feedstock (straw) and the extrusion feeder are shown in **Figure 2**.



**Figure 1. Top-section of test-reactor.**



**Figure 2. Biomass feed and extrusion feeder.**

**1.** Chopped-straw was tested in a 1 MMBTU/hr test-reactor at a rate of 3 ton/day with the following results:

- a. >50% N<sub>2</sub> content
- b. <2% O<sub>2</sub>
- c. 1-5% CH<sub>4</sub>
- d. Energy Content = 110-120 BTU/scf
- e. Syngas quality was not calculated, nor was the conversion efficiency.

**2.** Thermal conversion efficiency of 50% for biomass-to-syngas, with total conversion to electricity with 30% efficiency is not supported by the results, but not discouraged either.

**3.** A Farm-scale Process Development Unit (PDU—6 ton/day, 300 kW electric) was designed and simple CAD drawings were produced. The PDU was designed for continuous operation and long-term life cycle projections. Conversion efficiency was not projected.

**4.** The cost for small-scale gasification equipment is approaching the performance objective of \$18k/ton/day feed capacity; therefore, scaling the equipment to 50 ton/day (2 MW<sub>e</sub> out-put) is expected to be economically feasible, based on cost quotations for 6 ton/day PDU.

**5.** Performance parameters for the circulation system were determined: six bed materials were circulated effectively in the test-reactor at temperatures above 1200F, circulation rates exceeding 4 pounds per second when compressed air input was 150 scfm.

**6.** A novel low-cost reactor construction method, using off-the-shelf flanged cast-iron spool-sections that bolt together, was successfully demonstrated. These heavy duty ductile-iron pipe sections were shown effective for high temperature applications.

## Conclusions

1. The basic concept was proven effective in terms of its mechanical and thermal-chemical performance; however, the specific goals for the syngas composition were not accomplished because air (and consequent diluent-nitrogen) was not excluded from the product gases. We built a pilot-scale system on a limited budget, and focused exclusively on demonstrating the preliminary system feasibility; excluding nitrogen during initial testing was not pursued in this program. However, the system is still being tested and developed for hydrogen production.
2. Thermal conversion efficiency for biomass-to-syngas was not measured; mass and energy balance data were not obtained and the conversion efficiency was not projected.
3. The operational experience has been used to design and construct a Farm-scale Process Development Unit (PDU—6 ton/day, 300 kW electric) that will be used for continuous test campaigns, and the subject data needed for to perform the mass and energy balance will be obtained and long-term life-cycle economic analysis will establish energy conversion efficiency.
4. Gasification equipment for a farm-scale unit was specified and equipment costs were obtained. The total projected cost for an installed system with 6 ton/day processing capacity is \$300k. This cost is approaching the performance objective of \$18k/ton/day feed capacity (\$450 per kWh for the gasification equipment); therefore scaling up to the next increment of 50 ton/day and 2 MW<sub>e</sub> should prove to be economically feasible.
5. Operation of the gasification system showed a high carbon-char production ratio relative to the feed in-put. The exact ratio of feed to char production was not measured, but it was clearly evident that char must be recirculated to the oxidation zone to improve carbon conversion. To improve net conversion efficiency, it was observed that any oxygen input to the system must be made to react with carbon-char through recycle means, rather than using typical methods that squander costly oxygen by reacting it with the product gases (that are more reactive.) This is shown conclusively by G. Chen, et al, in their extensive modeling work on staged gasification.
6. Air pressure (3-7 psig) required to power the nozzle that drives the novel solids circulation is less than required by other fluid-bed systems, demonstrating that this simple low-cost circulation design offers a significant improvement over more complex and costly multi-port fluidization methods.
7. A low-cost cast-iron material was successfully demonstrated, maintaining gasification temperatures of 1325F to 1350F. Flanged cast-iron pipe has also been selected for construction of the farm-scale system and should be considered by other for near atmospheric pressure thermal applications.
8. Operating a simple biomass-extrusion feeder was successfully demonstrated. Biomass projects that rely on chopped-straw and other low-density compressible feeds should consider extrusion-feeding as a viable alternative when compared to rotary-valves and other problematic mechanical barriers.
9. The operating parameters identified during preliminary testing of the gasification system were well within the ranges expected and are appropriate for thermal chemical conversion and should result in high conversion efficiency.

## **Recommendations**

The development objectives for the Taylor Energy gasification technology have shifted; the need to produce high-quality syngas is not perceived to be a requirement for integrated production of electricity and Renewable Fuels from biomass. The first-year objectives for the farm-scale test system are based on using air-blown technology that can be retrofitted with oxygen-enriched-air. It has been shown by others that Fischer-Tropsch liquids can be synthesized economically from syngas containing >50% nitrogen. In fact, a higher fraction of diesel fuel is produced when nitrogen is present in the syngas, and the process economics are attractive when the catalyst activity is high and single-pass synthesis methodology is used. Therefore, the use of oxygen-enriched air for gasification is a compromise that will result in the production of medium-quality synthesis gas, and this middle-of-the-road solution will probably offer the best economics for equipment at the scale appropriate for biomass feedstock conversion.

A gasification system is being constructed at 6 ton/day scale, integrate with a 300 kW electric generator and Cummings IC engine that will be tested at a farm-site near Spokane, WA. The budget for green-field construction and start-up of the gasification / power generation system is \$732,000. A Phase II program in the planning stage will focus on scaling the technology to 50 ton/day feed capacity with 2 MW electric out-put, and is intended for commercial demonstration in Southern California.

## **Public Benefits to California**

The tasks performed with funds provided by this EISG grant work have contributed to the development of novel low-cost thermochemical gasification hardware that is anticipated to enable the utilization of renewable and waste feedstocks that are currently underutilized for energy production.

The 31 million tons of organic residues identified above can be used for the production of 30 million barrels of oil (equivalent) each year, if an economic conversion technology can be demonstrated. Approximately 85,000 tons per day of organic feedstock (3,500 tons/hour) are available in California; enough renewable energy to produce 4,000 MW-hours of electricity. The Taylor Energy gasification technology, integrated with different end-use production technologies (electricity, Renewable Fuels, and chemicals) could capture half of the market opportunities within the next decade. The dollar-value of these California feedstocks, when converted into electricity (valued at \$0.05/kWh) is equal to \$200,000 dollars per hour, or \$ 1.6 billion dollars per year. Assuming 50% market penetration, half the dollar value equals \$800 million dollars per year.

Rate payers would benefit significantly from the use of valuable energy resources, which are produced in California and would be converted into energy products within the State of California, thereby improving the economy and increasing energy security within the State. Further development and demonstration of the subject gasification technology is required. Nevertheless, the work performed to date, using ESIG funds, has demonstrated the basic feasibility of a gasification concept that has a high probability to advance the state-of-the-art and enhance the economic conversion of biomass to hydrogen. Much work remains to be done and the work is continuing on two fronts: the existing hardware is be developed for hydrogen production using a calcium carbonate cycle, and a new Transport Reactor design was developed and the hardware is being constructed at farm scale for testing during 2006.

## Introduction

California has abundant renewable energy resources. For example, more than 31 million tons of organic material, including paper, wood, and urban green waste, were disposed of in California landfills in 2003. California has passed legislation to encourage utilities to purchase electricity generated from renewable resources. Nevertheless, almost zero new capacity is being constructed in California that can utilize renewable biomass and other renewable energy feedstocks.

California already has significant installed capacity that relies on biomass feedstocks, using traditional Rankine cycle steam plants, which capacity was constructed during former decades when 10-year purchase contracts were available for about 12 cents per kWh. Most of those steam plants were designed to burn agricultural and forest residues and were in the <25 MW size range, with conversion efficiency around 20-25%. After the expiration of high-priced power contracts, known as “the cliff”, essentially all of those biomass plants were closed down for some period until recent incentives were offered for electricity generated using renewables.

Presently, most of the old steam plants that are permitted to burn biomass are in continuous operation. Their economics are favorable because the cost of their capital assets was already written down during the prior years of operation. However, the operating cost for a Rankine cycle steam plant (excluding capital) is still about 5 cents per kWh. Utilities are buying renewable power in the >7 cent per kWh range. Most of the old plants have been able to operate in the current business cycle and contribute a significant portion of renewable power to meet utility requirements, competing successfully with wind, solar, geothermal, and hydroelectric power.

Using existing steam technologies it is not likely that new biomass capacity will be built in California because the economics do not justify the capital expenditure. However, there are new thermal processing technologies on the horizon, including emerging thermal conversion technologies, advanced gasification methods are an attractive alternative to landfilling and could provide much needed electricity using renewable energy feedstocks.

The promised benefit from gasification technology is the ability to convert difficult solid fuels into clean gaseous fuel that can then be burned safely in traditional prime movers, including very large diesel (HCCI) engines and gas turbines; both turbines and reciprocating engines provide significantly higher net conversion efficiency to electricity than steam cycles, and the total system capital cost has the potential to be much lower as well. Furthermore, emerging Solid Oxide Fuel Cells (SOFC) will require gaseous fuels because solid fuels cannot be used to power SOFCs.

However, the promise of lower-capital cost conversion of biomass via gasification has not yet been realized. The significant potential is based on the fact that gasification systems process only 1/3rd to 1/5th the gas volume processed during combustion because most of the air is excluded; gasification equipment should be less costly in direct proportion to gas volume processed.

Gasification equipment has not proven to be less costly than traditional combustion equipment. In fact, it has been proven to be about the same or higher priced for the same fuel-feed capacity. This is partially due to the novelty of fluid-bed and entrained-flow gasification systems and partly due to the complexity of all existing gasification technologies, except small-scale down-draft systems, which have a long history of successful operation at relatively small-scale, but have serious limitations when applied at the large industrial scale needed to impact California.

Because of the lack of economically useful gasification technology identified above, a general objective of this project was to demonstrate technical and economic feasibility of a novel process for low-cost conversion of biomass into syngas suitable for power generation integrated with Renewable Fuels synthesis.

Gasification offers the potential for low-cost conversion of biomass resources into clean-fuel, while presently no economical solutions are clearly demonstrated. The proof of this statement is found partly in the facts that abundant biomass feedstocks are going to landfill in California and almost zero new capacity for biomass gasification is being constructed. Thermal conversion of biomass via gasification methodologies offer the best potential for economic utilization of renewable biomass via conversion into high-value products that are co-produced with electricity.

For example, the integration of a 20 MWe biomass fueled power plant with a Renewable Fuels facility, making mixed alcohols from biomass, would be an excellent approach because the power plant would consume lean tail-gas from a once-through catalytic synthesis plant making automotive fuel to meet the anticipated federal Renewable Fuels standard for blending agents.

A novel gasification approach was identified with the following design objectives:

- Eliminate the need for costly oxygen to make high-quality synthesis gas, (which was not achieved during this work.)
- Lower the complexity of the thermal conversion methodology.

Both these endeavors would result in the reduction of capital and operating costs.

## **Project Objectives**

The goal of this project was to demonstrate the feasibility of a novel biomass-to-syngas process specifically designed for low-cost conversion of biomass into high-quality syngas suitable for Solid Oxide Fuel Cell (SOFC) power generation.

1. Produce syngas from 3 different feedstocks in a 1 MMBTU/hr test reactor with:
  - a. 5-10% N<sub>2</sub> content
  - b. <1% O<sub>2</sub>
  - c. 1-5% CH<sub>4</sub>
  - d. Energy Content = 200-350 BTU/scf
  - e. Quality of 12.0 or higher ((H<sub>2</sub> +CO)/(CO<sub>2</sub>+H<sub>2</sub>O))
2. Verify thermal conversion efficiency for biomass to syngas of 50%, with total conversion to electricity efficiency of 30%.
3. Extrapolate bench scale data to the farm scale and confirm projected system conversion efficiency of 70% (biomass-to-syngas) with total conversion to electricity of 42%.
4. Demonstrate probable cost of 3-5 cents/kWh and total capital cost of \$18k/ton/day for farm scale units.

## **Project Approach**

The project was accomplished by performing the following tasks:

### **1) Design the pilot-scale reactor and related sub-systems necessary for testing.**

The reactor design evolved significantly after proposing the initial concept, in that the solids recirculation system was modified by moving the external oxidation leg into a concentric position located inside the gasification reactor. See Figure 3, where a 2" ID x 20' tall draft-tube is located concentrically within the columnar shaped reactor. It was anticipated that heat-losses from the oxidation section could thus be eliminated and the reactor construction would also be simplified.

Cold-flow testing was performed by simulating this reactor configuration, using an internal draft-tube for solids circulation. The simulation was performed at the same scale intended for pilot-plant construction and solids were easily circulated at a rate of 1 pound per second; after completing the cold-flow testing, the original design was modified to incorporate the use of an internal draft-tube for solids circulation. The cold-flow model is shown in Appendix Figure 5.

When making this design change, it was anticipated that separating the syngas product from the oxidation exhaust would be somewhat more difficult than in the original design; but the trade-off of eliminating the heat-loss from the oxidation leg was expected to be well worth the additional complexity imparted to the syngas separation and recovery system.

### **2) Fabricate a 1 MM BTU/hr test reactor.**

Selecting a novel method for constructing a low-cost gasification reactor was proposed. Several approaches were considered, and ultimately a construction method using cast-iron spool sections was selected and used for construction. The cast-iron pipe sections were bolted together to form the body of the reactor and proved to be air tight and capable of sustaining high-temperature operation. Ceramic fiber insulation was wrapped around the exterior of the reactor to provide insulation. The cast-iron spool sections can be seen in Appendix Figure 6. The cost for constructing the reactor using this approach was very low when compared to traditional methods, and the same approach is being used to construct the two-fold scale-up system.

It was also necessary to construct a cyclone and a flare-station in order to treat the product gas. All design work was performed by Taylor Energy. Concrete pads were poured, cranes were used to set equipment, and ducts were connected for these ancillary equipment systems. The cyclone with ducting is shown in Appendix Figure 7. The low-BTU gas flaring system is shown in Appendix Figure 8. The cost of these subsystems was not included in the original estimates. The final embodiment can be considered a "gasification facility," and the work was performed using a "total systems" approach, rather than focusing on the development of key elements.

### **3) Fabricate the support-structure and install the test reactor in the support structure.**

Even though the internal diameter of the reactor was only 8 inches, the reactor was approximately 27 feet in height in order to simulate a large-scale system. Therefore, the weight was quite significant, being over 5,000 pounds. An off-the-shelf structure made primarily of 4"x 4" angle iron, based on components used to construct grain elevators, was selected for housing the reactor.

The support-structure was 30' tall, with platforms located at 10' intervals. The support tower is seen in Appendix Figure 9, showing the use of galvanized steel construction throughout. Thermocouples and gas sample ports were installed in the reactor at sixteen locations, from top to bottom. The gasification reactor and support-structure were constructed inside an existing building located at the Western Research Institute test-site in Laramie. The reactor had to be housed inside because of the extremely cold winter temperatures typically experienced in Wyoming. The height of the building was necessarily increased 12 feet to accommodate the reactor height.

#### **4) Develop a test plan.**

A test plan was developed for start-up and shake-down activities. Particular emphasis was placed on operational safety, considering that the product gas contains high levels of carbon monoxide, which can be toxic to humans because it binds preferentially to hemoglobin. Forced air ventilation was added to the building and CO monitors were strategically located around the reactor at multiple levels. The product gases can also be explosive under adverse conditions. Provisions were made for explosion venting at the top of the reactor. The cyclone, which was located outside the building, was also constructed with appropriate explosion ports.

A detailed text-matrix was not prepared because the project funds were nearly expended completing the start-up, shake-down, and basic proof-of-concept activities. One may consider that the data acquired was somewhat preliminary in substance when compared to a typical test matrix that would be performed to fully characterize a gasification system. For example, the only biomass feedstock tested was grass-straw, and neither green waste nor forest residues were tested because the projects funds were committed to higher priority items (completing construction.)

#### **5) Start-up the system and conduct pilot-scale testing.**

System start-up required a number of significant iterations:

- The extrusion-feeder was initially difficult to operate, and forming a plug-seal against syngas loss to the atmosphere was troublesome to achieve. The first extrusion feeder embodiment is shown in Appendix Figure 10, and final configuration used successfully for extrusion-feeding of chopped grass-straw is shown in Appendix Figure 11.
- The preheat burner was constructed in three successive configurations before it operated successfully. The initial in-line pre-burner design is shown in Appendix Figure 12; the internal flame-holder that was ultimately used is shown in Appendix Figure 13, and the final pre-heat Burner configuration is shown in Appendix Figure 14.
- The diameter of the reactor was eventually increased from 8" to 12" in the bottom sections, from just above the feeder to the bottom of the reactor, to accommodate feeding of the very low-density grass straw. The design of the initial reactor with 8" ID is shown in Figure 15, and expanded reactor with 12" ID sections is shown in Figure 16.
- The draft-tube, constructed of iron with 9%-chrome 1%-molybdenum, was actually ignited and 15 feet of it melted and burned during an early start-up sequence before the operating procedures were clearly comprehended. A section of the draft-tube that was melted into the ceramic balls (used as the circulation media) is shown in Figure 17, and final nozzle with draft-tube that operated successfully is shown Figure 18.

- It was determined that significantly more funding would be required to operate the draft-tube configuration while separating the oxidation and gasification streams; therefore, all proof-of-concept testing was performed by analyzing and evaluating gas compositions of the combined gas streams that included nitrogen from the oxidation exhaust. That is, the gaseous effluent from the draft-tube (the oxidation leg) was mixed with the gasification products (reducing gases) that were generated in the annular space surrounding the draft-tube. We built the system and ran out of funds during the 1st phase for appropriate tests.
- The system was also operated as an entrained-flow reactor, without using the internal draft-tube for solids circulation. In this way, the baseline operating characteristics of the reactor were tested using a more traditional gasification mode and the temperature profile with and without the draft-tube was observed and evaluated.

All told, the start-up, shake-down, and preliminary testing activities, consumed the bulk of the project efforts as well as the majority of the funding resources.

#### **6) Evaluate and analyze pilot-scale performance data.**

After completing the start-up and shake-down activities, the system was operated successfully, both with and without the draft-tube (used for internal solids circulation); test data including temperature profiles and gas composition, were collected and the data were analyzed.

Carbon conversion emerged as a key issue during testing. The carbonaceous-char production was not well characterized in a quantitative manner. It was evident from rough weight measurements of the ash/char product that char formation was in excess of 15 % of the biomass in-put, and significantly above a 3% rate that would be appropriate for commercial operation of an ideal gasification system.

#### **7) Design a Farm-Scale system for continuous operation and long-term testing.**

Based on the operating experience gained during this development program and on the preliminary testing activities, a farm-scale unit was designed, which unit has a feed capacity of 6 ton/day--twice the capacity of the 3 ton/hr pilot-plant constructed at WRI.

The system is designed for continuous operation and to accomplish long-term testing objectives. Therefore, provisions have been made for bulk product storage in a dry location and continuous automatic feeding is also provided. The system is intended to operate during test-campaigns that last for 75 hours or more, so that equilibrium conditions are well established and the data will be predictive of long-term operating conditions. The temperature and product-gas data acquisition systems are also specified for continuous operation.

#### **8) Perform a cost analysis, including construction cost, and estimate the cost per kWh.**

A detailed analysis of the construction cost was performed. The hardware cost analysis was based on firm quotations for hardware scaled for the farm-size test unit. Operating costs (on a kWh basis) were not projected with accuracy because a system heat and energy balance was not well characterized. However, the system capital-cost has historically been the most significant factor in degrading total gasification system economics, and potential for a low-cost system has been demonstrated. Labor and fuel contribute about 50% to operating costs and are project specific.

## Project Outcomes

EISG funds (\$75k) were leveraged into a total \$375k project budget and were used to construct the subject pilot-scale test-reactor, which was used perform start-up testing to establish preliminary feasibility.

The preliminary feasibility of a novel gasification reactor concept was sufficiently verified by constructing and operating a test-reactor at large bench-scale, such that additional funding has been awarded by the USDA to continue development of the existing hardware (intended for hydrogen production,) and based on the operating experience a Transport Reactor design has been completed and is being constructed at farm-scale for long-term testing and development.

**1.** Chopped-straw was tested in a 1 MMBTU/hr test-reactor at a rate of 3 ton/day with the following results:

- a. >50% N<sub>2</sub> content
- b. <2% O<sub>2</sub>
- c. 1-5% CH<sub>4</sub>
- d. Energy Content = 110-120 BTU/scf
- e. Syngas quality was not calculated

**2.** Thermal conversion efficiency of 50% for biomass-to-syngas, with total conversion to electricity with 30% efficiency is not supported by the results, but not discouraged either.

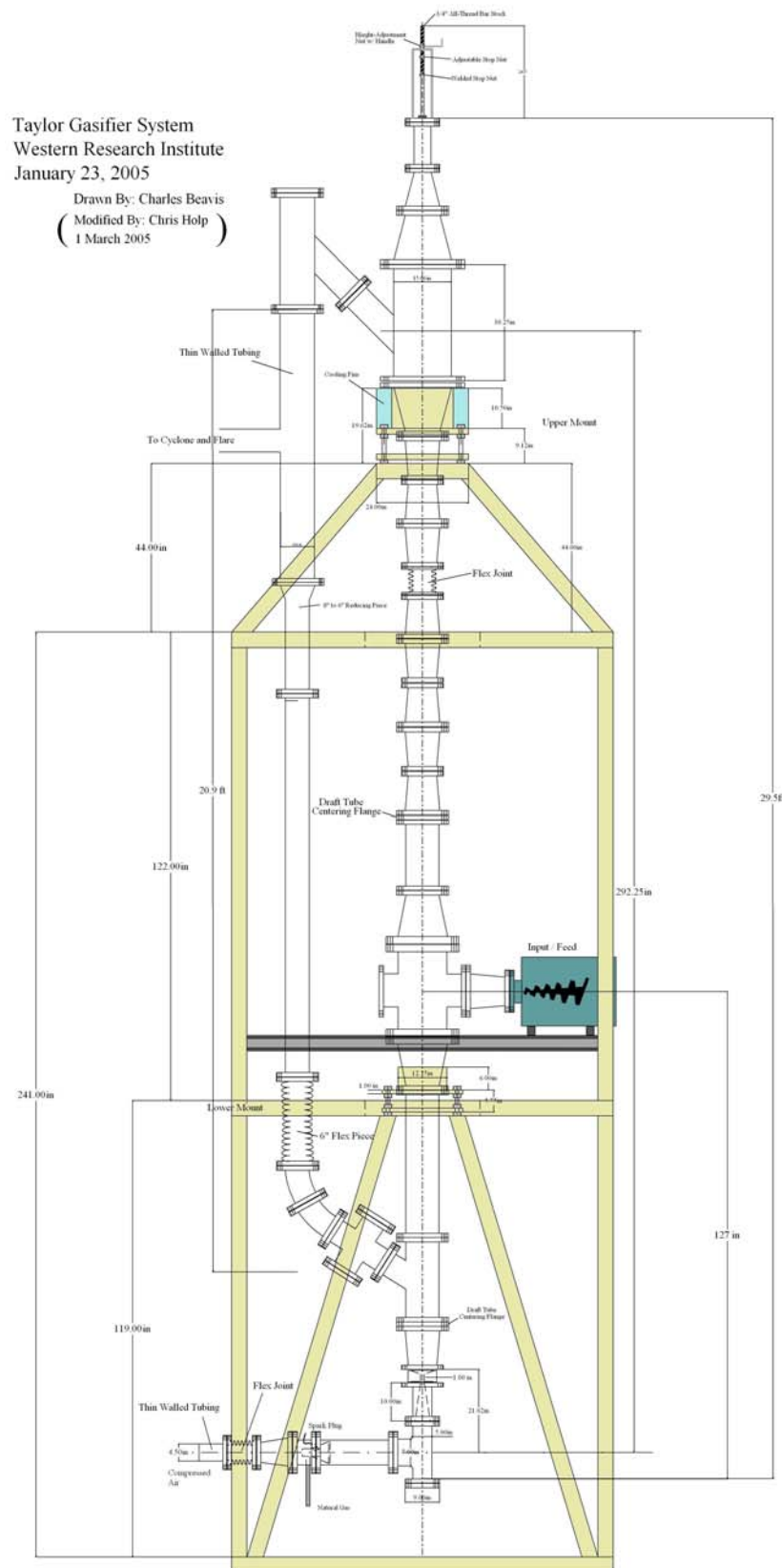
**3.** A Farm-scale Process Development Unit (PDU—6 ton/day, 300 kW electric) was designed and simple CAD drawings were produced. The PDU was designed for continuous operation and long-term life cycle projections. Conversion efficiency was not projected. An elevation drawing for the farm-scale PDU is shown in **Figure 3**.

**4.** The cost for small-scale gasification equipment is approaching the performance objective of \$18k/(ton/day) feed capacity; therefore, scaling the equipment to 50 ton/day (2 MW<sub>e</sub> out-put) is expected to be economically feasible.

**5.** Performance parameters for the circulation system were determined: six bed materials were circulated effectively in the test-reactor at temperatures above 1200F, circulation rates exceeding 4 pounds per second when compressed air in-put was 150 scfm. Materials circulated successfully included three ceramic materials (balls—10 mm, 3 mm, and 1 mm) and three steel materials (balls--10 mm, 7 mm, and 2 mm). The ceramic materials were comminuted too rapidly for commercial use.

**6.** A novel low-cost reactor construction method, using off-the-shelf flanged cast-iron spool-sections that bolt together, was successfully demonstrated. These heavy duty ductile-iron pipe sections were shown effective for high temperature applications.

Figure 3. Elevation drawing for Farm-Scale PDU



Recirculation of the media was first accomplished on November 22<sup>nd</sup>, 2004. The first heat-up of the reactor was conducted on December 10<sup>th</sup>, 2004. The first experiment including the feed of straw occurred on December 16<sup>th</sup>, 2004. The next period included a number of experiments in which the variety of media were investigated, the problems with feeding straw into the smaller eight inch cross-section and the natural gas plumbing was completed. The draft-tube was replaced after the excess heating incident, and the preheat burner was modified.

The first gas product tests were conducted on February 9<sup>th</sup>, 2005. These gas samples were taken from the same position as TC3. The reactor was partially filled with 2 mm carbon steel media and the position of TC3 was above the media bed. The gas composition only showed nitrogen, oxygen, carbon dioxide and water as to be expected without effort to separate pyrolysis products from the air and oxidation products. After these experiments the reactor was filled to just below the feeder with the smaller steel shot media (2 mm).

The first two experiments that included all the reactor modifications, the smaller media, the improved insulation and the media bed up to the feeder were conducted on February 22<sup>nd</sup> and February 23<sup>rd</sup>, 2005. The two experiments were similar in that there was an initial period of reactor heat up followed by a period of straw feed. Each experiment lasted approximately 6 hours. Combustible fuel-gas flowing from the mid-section of the reactor is shown in **Figure 4**.

#### February 22, 2005

The profiles of the thermocouple-measured temperatures versus time were logged. For the portion of the lower reactor in which pyrolysis occurred (TC2, TC3, TC4) the temperatures ranged from 500°F to 800°F. Straw feed was begun at 140 minutes at a motor frequency of 14 Hz that corresponds to a feed rate of 4.8 pounds of straw per minute. The airflow rate was 120 scfm. The GC data was also collected periodically. Dry analysis of the sample gases is shown in the following table with numbers equal to volume percent. The first sample was after straw feed was initiated; the later samples were after feed had occurred for two hours. The straw feed was at a lower level for this experiment, approximately 150 pounds per hour.

Table 1

Sample #	Time	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO	CH <sub>4</sub>	CO <sub>2</sub>
A2	130	0.5	77.7	0	3.4	0.5	18.7
C	270	1.0	56.4	2.5	10.1	0.9	29.1
D	277	0.9	57.3	0	10.0	0.7	31.0

February 23, 2005

The profiles of the thermocouple-measured temperatures versus time were logged. For the portion of the lower reactor in which pyrolysis occurred (TC2, TC3, TC4) the temperatures ranged from 500°F to 800°F. The feed rate for sample B was 21 Hz (motor frequency equal to a straw feed rate of 5.6 lbs/min), the feed rate for sample C was 30 Hz (8.2 lbs/min), and the feed rate for samples D, E and F was 40 Hz (11.3 lbs/min). The gas results for samples B and C were similar to samples C and D for the 2/22 experiment under the same conditions. The airflow and natural gas feed were reduced before samples E and F, although those effects were less obvious in the sample gas concentrations than the increase in straw feed rate. Samples D and E produce Higher Heating Values just over 100 BTUs/scf.

Table 2

Sample #	Time	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO	CH <sub>4</sub>	CO <sub>2</sub>
B	215	0.5	54.4	0	10.5	0.9	32.8
C	235	0.9	59.5	0.5	9.5	1.6	28.0
D	255	2.7	31.1	2.1	17.0	4.7	42.9
E	275	3.5	44.4	2.7	11.8	5.7	32.3
F	300	1.6	37.3	3.0	15.5	3.6	39.4



Figure 4. Fuel-gas flowing from reactor mid-section

## Conclusions

1. The basic concept was proven effective in terms of its mechanical and thermal-chemical performance; however, the specific goals for the syngas composition were not accomplished because air (and consequent diluent-nitrogen) was not excluded from the product gases. Due to budget constraints, the focus was exclusively on demonstrating the preliminary system feasibility and excluding nitrogen during initial testing was not pursued.
2. Thermal conversion efficiency for biomass-to-syngas was not projected; mass and energy balance data were not obtained and the conversion efficiency was not projected. However, there were no results that indicated efficiency would be lower than the target.
3. The gasification system did not reach equilibrium during the series of 8-10 hour test runs performed during shake-down and start-up. It was determined that test campaigns that last 75 to 100 hours are needed to reach equilibrium within the system. Therefore, an energy balance was not achieved and conversion efficiency was not projected. A Farm-scale Process Development Unit (PDU—6 ton/day, 300 kW electric) is being constructed that will be used for continuous test campaigns, and the data will be used for long-term life-cycle economic analysis and to establish energy conversion efficiency.
4. Gasification equipment for a farm-scale unit was specified and specific equipment quotations were obtained from equipment vendor for all subsystems. The total projected cost for an installed system with 6 ton/day processing capacity is \$300k. This cost is still high at this small scale, but is approaching the performance objective of \$18k/(ton/day) feed capacity; therefore, further scaling to the next increment of 50 ton/day and 2 MWe should prove to be economically feasible.
5. Operation of the gasification system showed a high carbon-char production ratio relative to the feed in-put. The exact ratio of feed to char production was not measured, but it was clearly evident because of the quantity produced that char must be recirculated to the oxidation zone to improve carbon conversion.
6. Air pressure (3-7 psig) required to power the nozzle that drives the novel solids circulation is less than required by other fluid-bed systems, demonstrating that this simple low-cost circulation design offers a significant improvement over more complex and costly multi-port fluidization methods.
7. A low-cost cast-iron material was successfully demonstrated, maintaining gasification temperatures of 1325F to 1350F. Flanged cast-iron pipe has also been selected for construction of the farm-scale system and should be considered by other atmospheric pressure thermal applications.
8. Operating a simple biomass-extrusion feeder was successfully demonstrated. Biomass projects that rely on chopped-straw and other low-density compressible feeds should consider extrusion-feeding as a viable alternative when compared to rotary-valves and other problematic mechanical barriers.
9. The operating parameters identified during preliminary testing of the gasification system were well within the ranges expected and are appropriate for thermal chemical conversion and should result in high conversion efficiency.

## Recommendations

The development objectives for the Taylor Energy gasification technology have shifted; the need to produce high-quality syngas is not perceived to be a requirement for integrated production of electricity and Renewable Fuels from biomass. The first-year objectives for the farm-scale test system are based on using air-blown technology that can be retrofitted with oxygen-enriched-air. It has been shown by others that Fischer-Tropsch liquids can be synthesized economically from syngas containing >50% nitrogen. In fact, a higher fraction of diesel fuel is produced when nitrogen is present in the syngas, and the process economics are attractive when the catalyst activity is high and single-pass synthesis methodology is used. Therefore, the use of oxygen-enriched air for gasification is a compromise that will result in the production of medium-quality synthesis gas, and this middle-of-the-road solution will probably offer the best economics for equipment at the scale appropriate for biomass feedstock conversion.

A gasification system is being constructed at 6 ton/day scale, integrate with a 300 kW electric generator and Cummings IC engine that will be tested at a farm-site near Spokane, WA. The budget for green-field construction and start-up of the gasification / power generation system is \$732,000. A Phase II program in the planning stage will focus on scaling the technology to 50 ton/day feed capacity with 2 MW electric output, and is intended for commercial demonstration in Southern California.

## Public Benefits to California

The tasks performed with funds provided by this EISG grant work have contributed to the development of novel low-cost thermochemical gasification hardware that is anticipated to enable the utilization of renewable and waste feedstocks that are currently underutilized for energy production.

The 31 million tons of organic residues identified above can be used for the production of 30 million barrels of oil (equivalent) each year, if an economic conversion technology can be demonstrated. Approximately 85,000 tons per day of organic feedstock (3,500 tons/hour) are available in California, equivalent to 42 billion BTU/hr; enough renewable energy to produce 4,000 MW-hours of electricity.

The Taylor Energy gasification technology, integrated with different end-use production technologies (electricity, Renewable Fuels, and chemicals) could capture half of the market opportunities within the next decade. The dollar-value of these California feedstocks, when converted into electricity (valued at \$0.05/kWh) is equal to \$200,000 dollars per hour, or \$ 1.6 billion dollars per year. Assuming 50% market penetration, half the dollar value equals \$800 million dollars per year.

Rate payers would benefit significantly from the use of valuable energy resources, which are produced in California and would be converted into energy products within the State of California, thereby improving the economy and increasing energy security within the State. Further development and demonstration of the subject gasification technology is required. Nevertheless, the work performed to date, using ESIG funds, has demonstrated the basic feasibility of a gasification concept that has a high probability to advance the state-of-the-art and a bench-mark for the economic conversion of biomass to hydrogen using California feedstocks.

## Endnotes

1. *Report to the Legislature (2005)* Prepared by the California Integrated Waste Management Board (CIWMB), pursuant to a directive in Assemble Bill 2770, a statute written in 2002 (AB chapter 740) .
2. Prins, Mark J., Krzysztof, Ptasinski J.(2005) Exergetic optimization of a production process for Fischer- Tropsch fuels from biomass . *Fuel Processing Technology*. 2005, 86: 375-389.

## **Appendix**

**Figures 5 through 18 are photographs taken of hardware constructed during the performance of this project.**



**Figure 5. Cold-flow model circulating 10 mm steel balls**

Figure 6. Cast-iron spool-sections used to construct the reactor

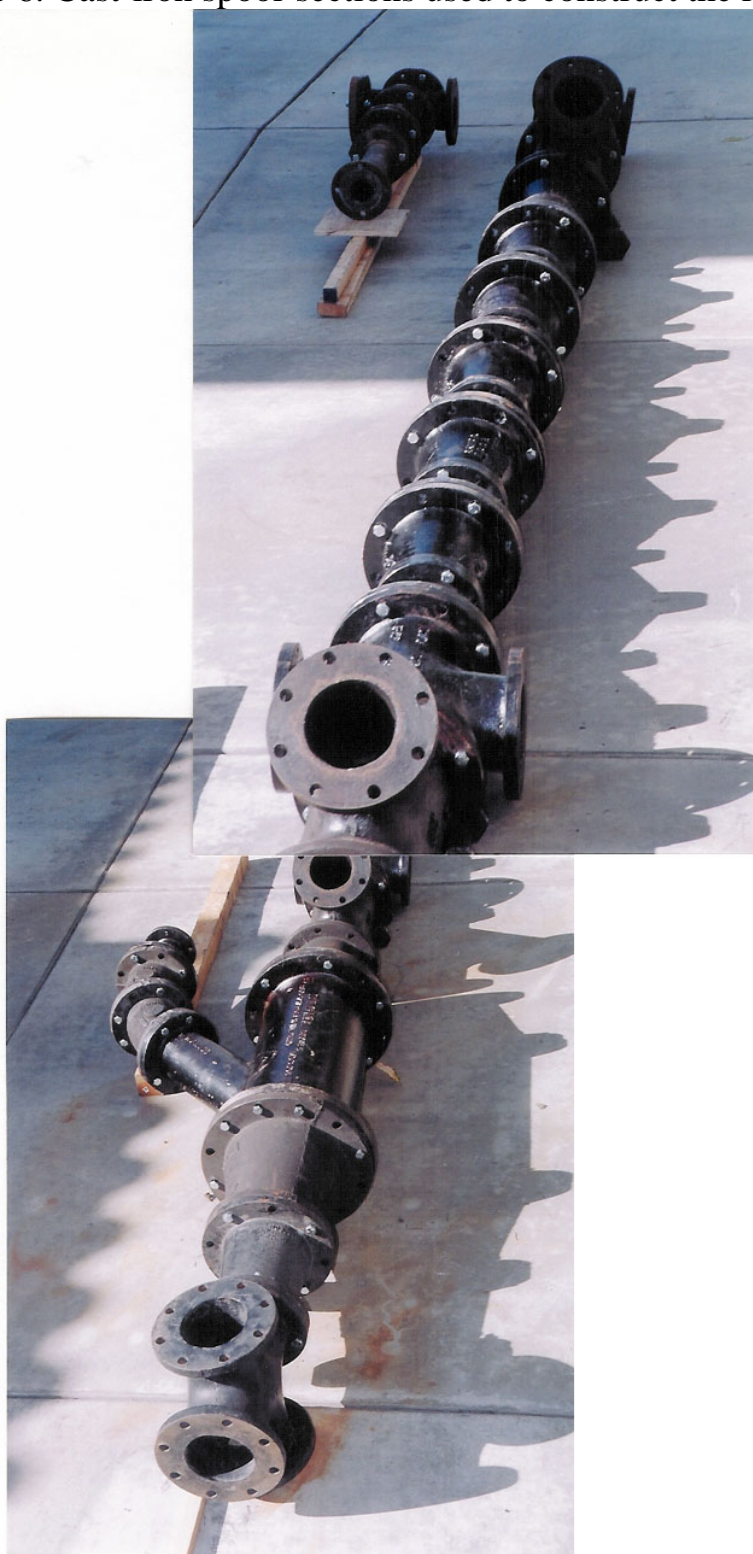


Figure 7. Cyclone used for carbon-char recovery



Figure 8. Low-BTU Flare used to combust product gases



Figure 9. 4" x 4" angle-iron tower used to support the test reactor



Figure 10. First Extrusion design with nearly straight discharge tube

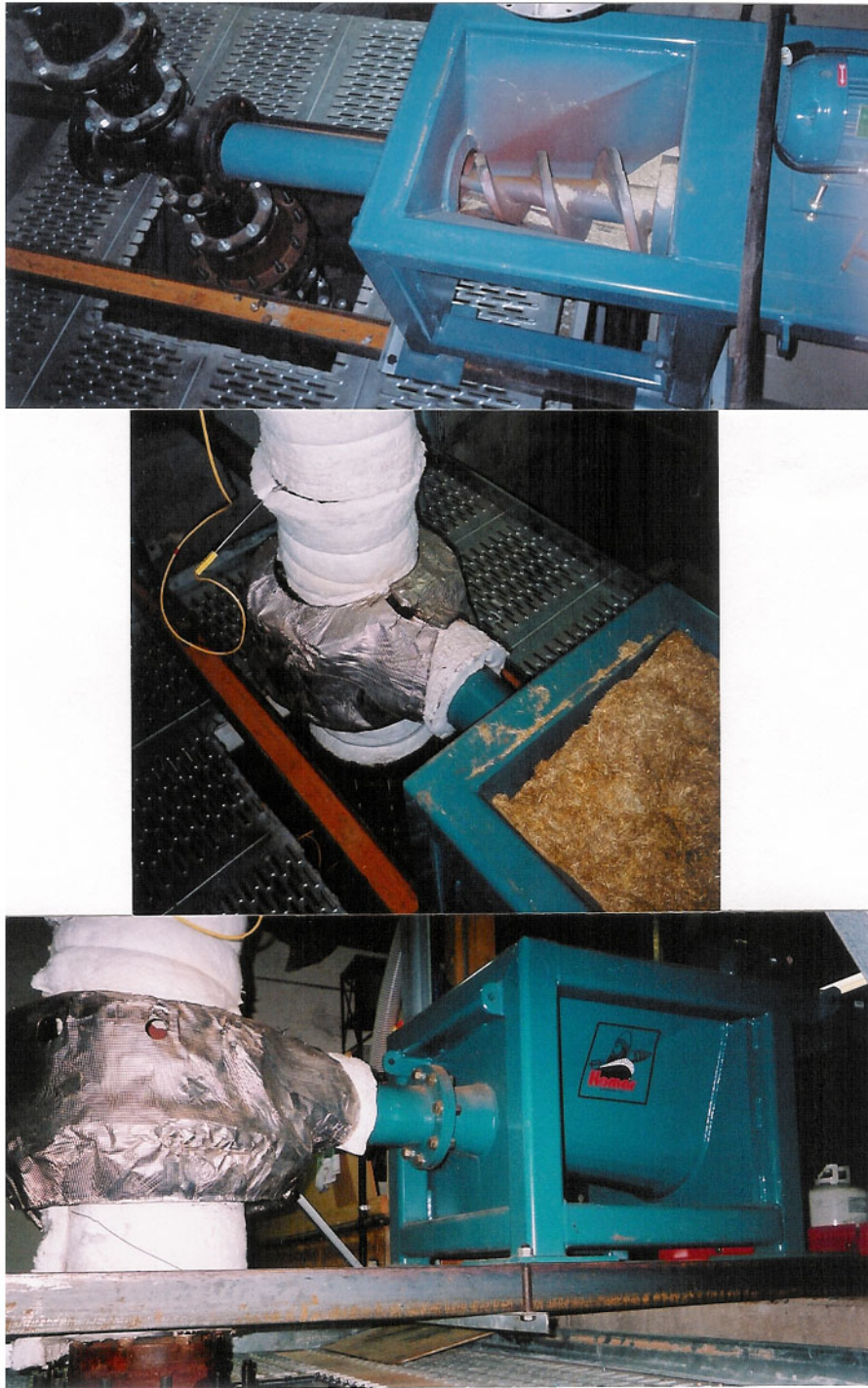


Figure 11. Final embodiment with convex extrusion tube

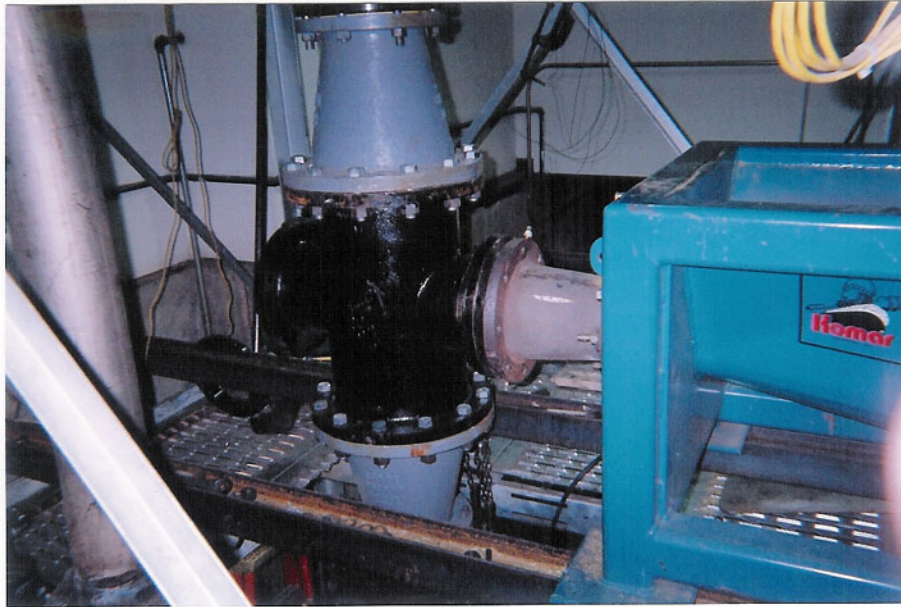


Figure 12. Initial in-line burner

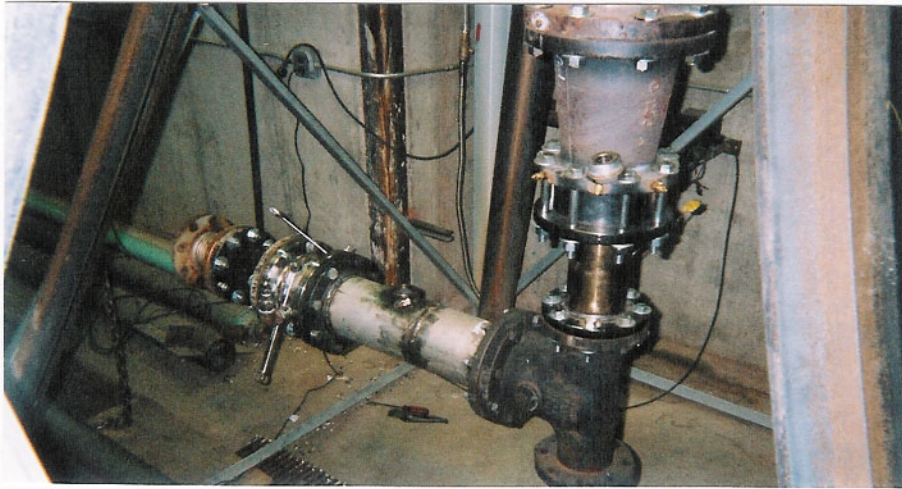


Figure 13. Flame holder located inside preheat burner

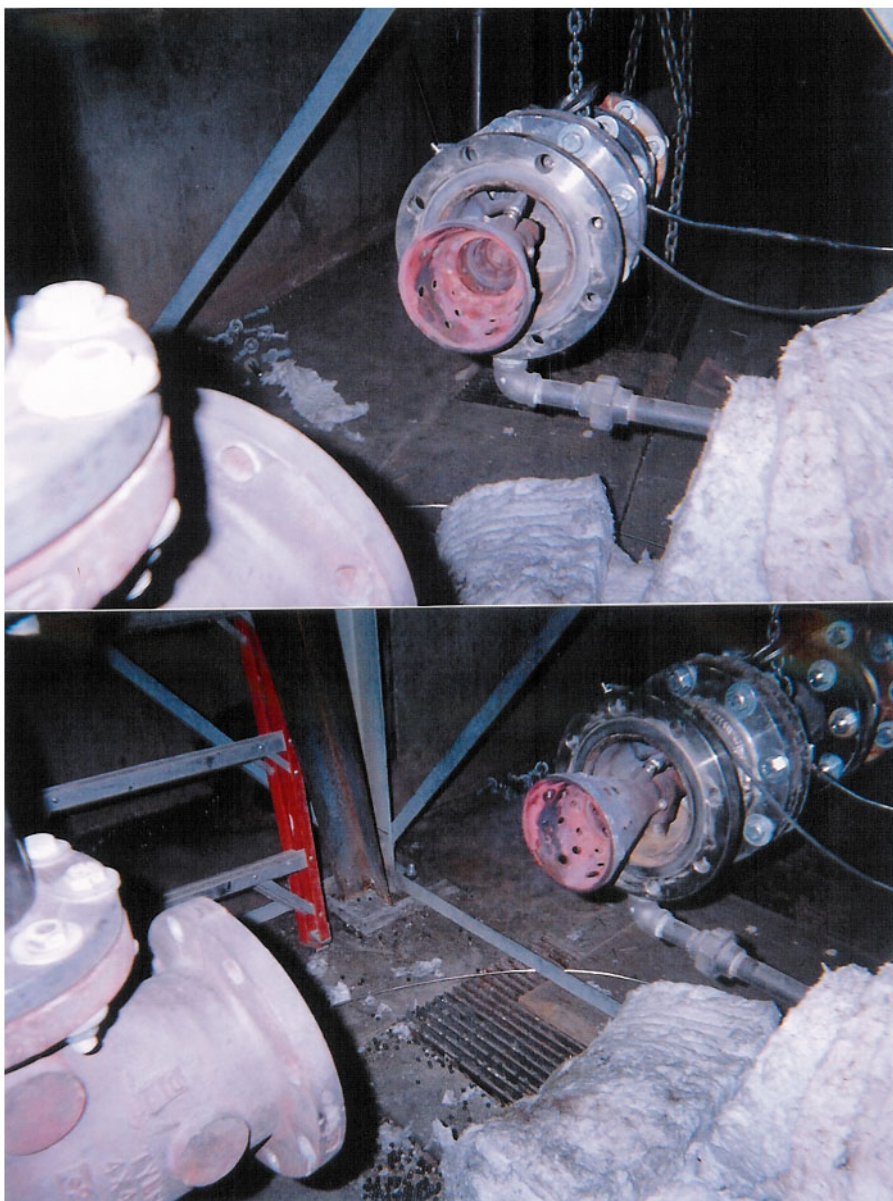


Figure 14. Horizontal preheat burner configuration

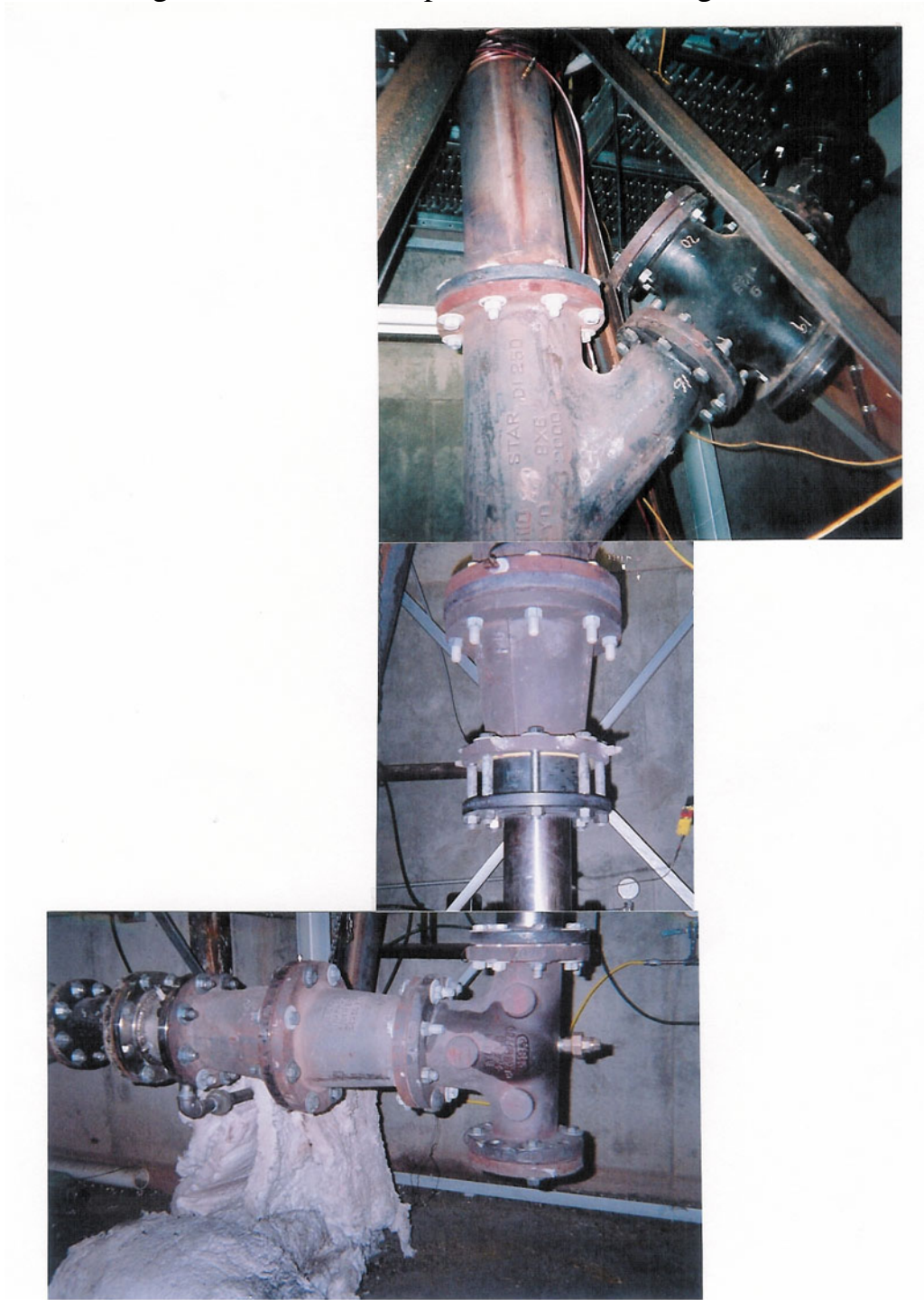


Figure 15. Initial 8 inch ID Pipe sections with concentric draft-tube

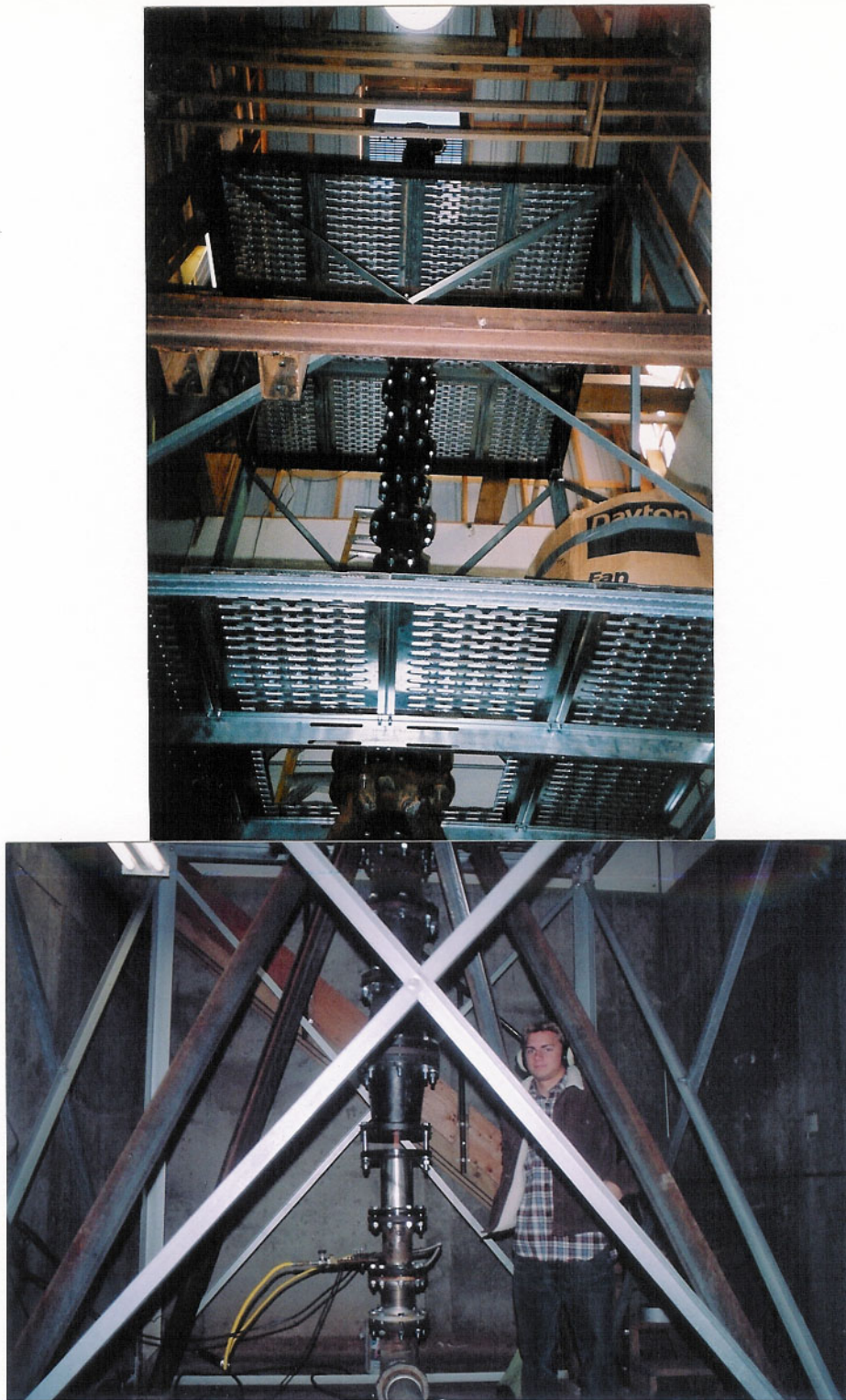


Figure 16. Reactor expanded to 12 inch ID with 2" ID draft-tube

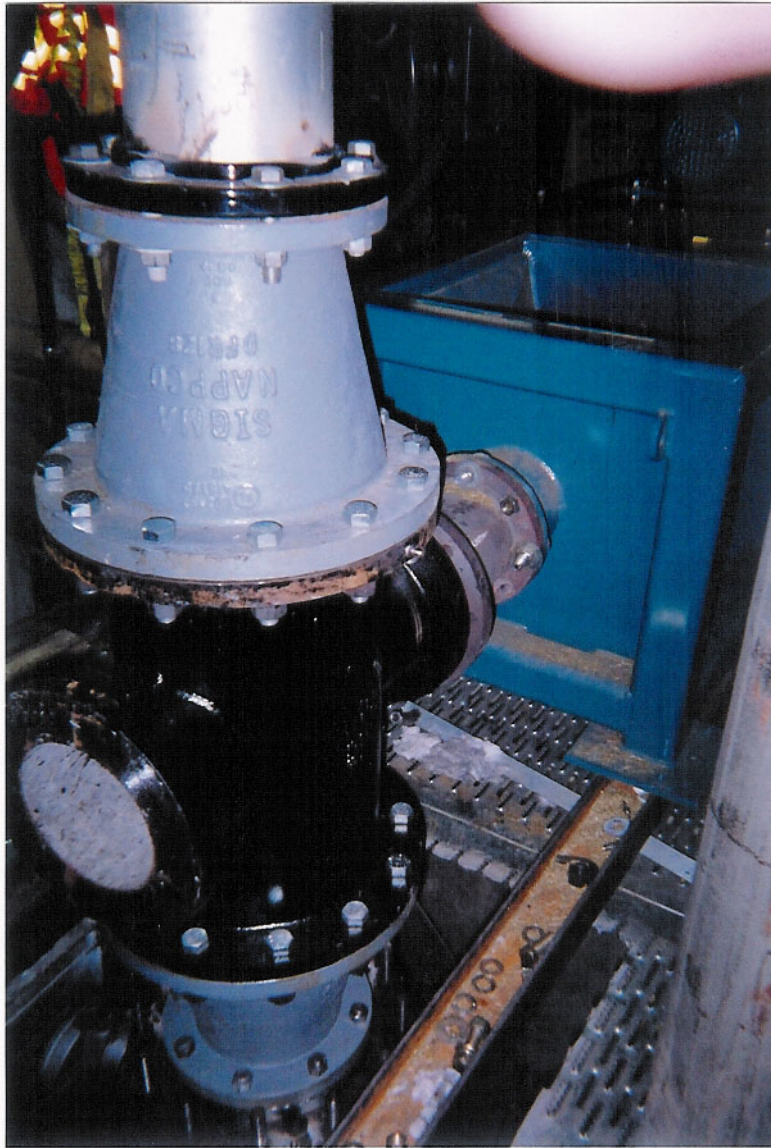


Figure 17. 10 mm ceramic balls and draft-tube were melted together during one difficult run, which problem was corrected during subsequent testing.

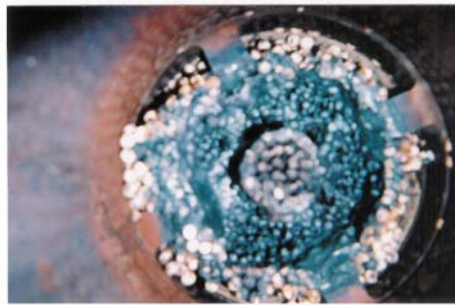
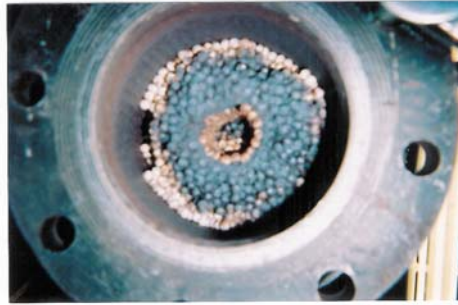
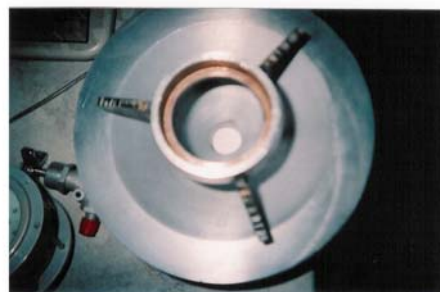
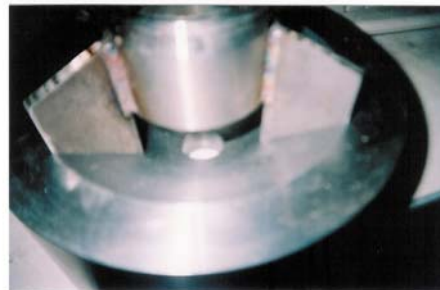


Figure 18. Successful Draft-tube base design with interlocking nozzle





**California Energy Commission**  
Energy Innovations Small Grant (EISG) Program  
**PROJECT DEVELOPMENT STATUS**

**Questionnaire**

Please Identify yourself, and your project: <b>PI Name</b> Donald G. Taylor <b>Grant #</b> 53427A/03-17	
<b>Overall Status</b>	
<b>Questions</b>	<b>Comments:</b>
1) Do you consider that this research project proved the feasibility of your concept?	<i>Yes. Preliminary feasibility has been demonstrated, but more extensive campaigns (75-100 hour tests) are needed to prove technical and economic feasibility during extended test campaigning.</i>
2) Do you intend to continue this development effort towards commercialization?	<i>Yes. This preliminary testing was accomplished at 250 pound/hour scale; additional testing is being performed on the test hardware focused on hydrogen production.</i>
<b>Engineering/Technical</b>	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	<i>Carbon conversion efficiency is the primary technical issue; char conversion efficiency must be improved significantly at pilot-scale by recycling carbon to the oxidation zone.</i>
4) Have you defined a development path from where you are to product demonstration?	<i>Yes. Small-scale systems are probably viable, but we intend to begin commercialization at 50 ton/day scale, which requires an 8 fold scale-up; we intend to build the first commercial demonstration in Southern California and have identified recyclable-residues as the feedstock and have a location in the Irvine, CA, sphere of influence; 300 ton/day scale is intended as the next increment.</i>
5) How many years are required to complete product development and demonstration?	<i>Three years time will complete the development and demonstration cycle. One year to complete the sub-scale testing using the 6 ton/day system producing 300 kWh, and two years to complete the 50 ton/day, 1.8 MWe demonstration.</i>
6) How much money is required to complete engineering development and demonstration?	<i>Approximately \$732k is committed to construct the 2<sup>nd</sup> generation unit to be used for test campaigns. About \$1.7mm will be needed to construct and test the first commercial unit; (\$900k for gasification hardware with 50 ton/day capacity) An additional \$1.3 million is needed for a 1.8 MW electric power generation system that will be financed.</i>
7) Do you have an engineering requirements specification for your potential product?	<i>No. Engineering specifications will be completed after performing additional testing at farm-scale. Engineering specifications have been developed for the 6 ton/day farm-scale test unit.</i>
<b>Marketing</b>	
8) What market does your concept serve?	<i>Agricultural, environmental, and industrial sectors.</i>

9) What is the market need?	<i>Feedstock availability is summarized in the California Integrated Waste Management report prepared for the California Legislature (2005). The need for electric power generation using renewable resources is generally well known in California, but market opportunities are all based on local requirements. For example, the City of Irvine has a specific need, as do other municipalities.</i>
10) Have you surveyed potential customers for interest in your product?	<i>Several specific opportunities have been identified, such as the City of Irvine's need relative to their North Wood 5 development, and several other municipal opportunities have been identified.</i>
11) Have you performed a market analysis that takes external factors into consideration?	<i>To some degree. However, we are not trying to capture all of the market; we only want to establish a reasonable number of near-term projects, probably located on existing landfill sites, such as the Bowerman Landfill located near Irvine where 6,000 tons/day of feedstock is available. Once a processing location is established, then growth in processing capacity is less impacted by external factors, such as competition.</i>
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	<i>Yes. All the typical barriers exist. We consider the barriers beneficial because competition is limited by barriers, particularly after a "first company" has data and experience and is able to surpass the obstacles, such as environmental permitting. Others tend to have more difficulty getting permitted in a specific geographic area.</i>
13) What is the size of the potential market in California for your proposed technology?	<i>Based on the availability of low-cost and negative-value feedstocks, and the market for electricity and Renewable Fuels in California, the markets are so large that growth limitations are based much more on organizational and capital constraints, rather than on market opportunities.</i>
14) Have you clearly identified the technology that can be patented?	<i>Yes. We have a novel processing configuration that can be patented. However, our objective is not necessarily to keep everyone else out of the market; we prefer to gain ascendancy in a particular geographic area by establishing operating equipment at an optimum location. Traditional barriers limit competition. (The equipment sales business is less interesting and more problematic.)</i>
15) Have you performed a patent search?	<i>Yes. The Principal Investigator is an expert in the field of gasification and has been paid to search the patent literature extensively several times during the course of 25 years experience; the PI holds one very good patent, and has experience working around the prior-art to obtain patent protection.</i>
16) Have you applied for patents?	<i>Not yet. However, US patents will be applied for within one year of the present time.</i>
17) Have you secured any patents?	<i>Yes, but not specifically addressing the most important innovations being developed. US # 5,584,255</i>
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	<i>This report discloses some elements that can be covered by a patent, but other key elements have not been disclosed in any public forum.</i>
<b>Commercialization Path</b>	

19) Can your organization commercialize your product without partnering with another organization?	<i>Partnering is being done on a limited case by basis. For example, Taylor Energy partnered with WRI to perform the feasibility work in Laramie. Taylor is partnering with Farm Power (Spokane, WA) to develop the farm-scale development system, and they will have rights to commercialize systems with less than 50 ton/day capacity (&lt;2.0 MWe).</i>
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	<i>Yes. For example, Davy Technologies, LTD. However, the time to secure a major industrial partner is after the technology has been demonstrated successfully at pilot-scale. We will have more leverage to structure a deal with a major partner after establishing a toehold in the market.</i>
21) Have you developed a commercialization plan?	<i>Yes. The commercialization plan is updated bi-annually. For example, if the President signs an energy bill, we may modify our plan if a near-term market for Renewable Fuels is established.</i>
22) What are the commercialization risks?	<i>The primary risk is that the Principal Investigator holds most of the intellectual properties, know-how, and trade-secrets, which must be transferred into a specific product embodiment and more technical knowledge transferred to the development team. Once the development team knows how to perform all the work, there are few risks, except possibly that oil prices could drop to \$21/bbl again.</i>
<b>Financial Plan</b>	
23) If you plan to continue development of your concept, do you have a plan for the required funding?	<i>We intend to request co-funding from the CEC via the PIER program, probably on the order of \$900k for the commercial demonstration at 50 ton/day scale (1.8 MW). Thereafter, project financing is available for this type of business where long-term contracts of 10 years or more are typically available for both energy feedstocks and energy products. Equity funding is possible as well, since Taylor Energy still holds all it's ownership equity.</i>
24) Have you identified funding requirements for each of the development and commercialization phases?	<i>Yes. The capital required to reach the 300 ton/day scale is quite significant; however, the returns at that scale are very attractive. And the business model will have been proven to be profitable at 50 ton/day scale.</i>
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	<i>Yes. We have received \$732k to continue development of the gasification technology by constructing a 2-fold scaled-up system to be located near Rockford, WA.</i>
26) What are the go/no-go milestones in your commercialization plan?	<i>Gasification development and subsequent commercialization are the only business activities in which Taylor Energy engages. We might run out of capital and be slowed down, but we're not going to stop development and commercialization for any reason.</i>
27) How would you assess the financial risk of bringing this product/service to the market?	<i>The financial risk is very low because the core technology (thermochemical conversion) is well understood; the key to the business is demonstrating a low-cost embodiment, which is the special expertise of the PI.</i>
28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	<i>Yes. A detailed plan has been prepared, based on commercialization a 300 ton/day facility that produces both electricity and Renewable Fuels, and includes detailed financial projections. This may be slightly premature for large-scale, but will be necessary after a 2<sup>nd</sup> generation plant is operational and the technical issues are largely resolved.</i>

<b>Public Benefits</b>	
29) What sectors will receive the greatest benefits as a result of your concept?	<i>Industrial and environment.</i>
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	This specific gasification technology, integrated with different end-use production technologies (electricity, Renewable Fuels, and chemicals) could capture half of the market opportunities within the next decade. The dollar-value of these California feedstocks, when converted into electricity (valued at \$0.05/kWh) is equal to \$200,000 dollars per hour, or \$ 1.6 billion dollars per year. Assuming 50% market penetration, half the dollar value equals \$800 million dollars/year.
31) Does the proposed technology reduce emissions from power generation?	<i>Renewable feedstocks reduce the emissions of greenhouse gases.</i>
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	A CIWM report to the California State Legislature concludes that, "Thermochemical technologies can process a wide variety of feedstocks and can have the greatest effect on landfill reduction. Thermochemical technologies can also produce a larger variety of products which can displace the need for non-renewable petroleum resources. Although for some stakeholders there are greater concerns with emissions from this family of technologies, the limited data that was acquired all indicate that emissions levels are below the regulatory limits placed upon them."
<b>Competitive Analysis</b>	
33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	<i>Cost-effective thermal conversion technology is not currently available at the scale appropriate for biomass processing. This business sector has been too small for established energy and A&amp;E companies, and too difficult for garage-scale developers; dozens have tried over the past two decades, and few or none have succeeded in North America where margins are slim compared to Japan and Europe, where more costly systems are available.</i>
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	<i>Atmospheric pressure operation of our reactor is thought to be a major disadvantage by many who typically want to integrate with gas turbines and synthesis technology. Ultimately, low-pressure equipment is less costly to construct and to operate, and will win in competition with pressurized systems when the feedstock cost is low.</i>
<b>Development Assistance</b>	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
35) If selected, would you be interested in receiving development assistance?	<i>Yes. PIER funding would help establish the technology at commercial-scale using a local feedstock at a Southern California venue. Market assessment and improving the business plan would also be very helpful.</i>